SYSTEMATIC FIXTURE DESIGN TO ADDRESS DEFICIENCIES IN DYNAMIC ENVIRONMENTAL TESTING

Smart Dynamic Testing Community of Practice
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Dynamic Vibration Environmental Testing (aka, dynamic environment testing) is a significant expense in the product development cycle, both in terms of the cost of the testing and also of the impact on the schedule. Failures during laboratory dynamic tests can multiply these expenses when one considers the impact to cost and schedule of unnecessarily needing to redesigning components, renegotiating testing contracts, etc. It is clearly problematic to over-test in the laboratory, as this often leads to unrealistic failures, and this occurs quite frequently in practice. Even more problematic, although much less common in practice, is the possibility that components could be under-tested and that they fail in service after passing the qualification test. This goes directly to not understanding the reliability of the hardware operating in the field (service) dynamic environment, which can be extremely expensive and may even lead to the loss of product and/or life. Thus, it is imperative that the test accurately represents the intended field (in-service) dynamic environment to avoid both unrealistic test failures and false positive test results.

One important consideration in design of a laboratory dynamic test is the test fixture that connects the test component to the excitation system. The cost of the test fixture, including design, fabrication, setup, and checkouts, can account for over 50 percent of the vibration test cost. However, if optimized, the return on investment is high when considering the influence of the test fixture on the quality of the test. Historically, test fixtures have typically been designed to be as stiff as possible in an attempt to drive the test fixture resonances above the frequency range of interest. It is recognized that this concept is based on an often false premise that the vibration levels are perfectly uniform at all payload attachment points. Recent works have begun to improve characterization of the field dynamic environment and provide a basis for optimizing attachment point impedances for an improved representation of the field dynamic environment in the test. Furthermore, in recent years the Smart Dynamic Testing (SDT) paradigm has gained traction; SDT is a test approach that utilizes analytical models to take full account of the influence of test fixtures and vibration generation devices on the dynamic response of the test structure to ensure that field (in-service) dynamic environment is accurately replicated in a controlled laboratory setting.

A panel of over 40 experts met as part of the SDT Community of Practice (CoP) to discuss the state-of-the-art in dynamic testing. After consideration, the SDT CoP recommends

further research in the area of test fixture design for dynamic testing[1]. This is timely because recent advances in SDT open up new possibilities and promise to shed new light on this problem. This white paper presents some of the justification for selecting this as a key area of interest.

1. Justification

The Group discussion uncovered many different issues related to current test fixture design practices and determined that a more comprehensive approach is required to advance the state of the art in dynamic testing. The concept of test fixture design needs to be expanded to include an overarching design of the dynamic test setup, consideration of complex configurations including multi-axis dynamic test specifications and a more rigorous link to the field dynamic environments definition including the concept of impedance.

The range of tests that the SDT CoP deals with varies widely, from a $10 component where very little is known about the field dynamic environment and there is little sensitivity to over-test, to multi-million-dollar vehicles with many complexities including nonlinearities, and extreme sensitivity to over-test, etc. State of the art in test fixture design varies as well, usually in proportion to the complexity and consequences of test failures. In single degree-of-freedom test cases where the test specification is a single vibration profile is defined for all attachment points, the approach of designing a test fixture with no resonances in the frequency band of interest may be appropriate and historically has been generally successful. Basic considerations of representative mounting structures can improve the fidelity of the test. However, this test approach cannot be expected to have high correlation to the true field dynamic environment. As the need to define the field dynamic environment more accurately increases, a more rigorous approach should be taken, including modeling to simulate the test, testing to characterize the test fixture response, and analysis through various techniques to validate the test approach. The SDT CoP recommends research that would elaborate on these advanced approaches, and also explore how they might translate to tests where far fewer resources are available.

Figure 1 shows an extreme example of testing a multi-million-dollar vehicle, in this case the European Service Module Structural Test Article (E-STA) mounted on the Mechanical Vibration Facility (MVF). MVF is a large multi-axis shaker system located at the NASA Glenn Research Center Neil A. Armstrong test facility where E-STA underwent sine vibration testing. This test was very heavily instrumented and undertaken to collect data at flight load levels to test durability, characterize component environments and for model updating of NASA's Multi-Purpose Crew Vehicle (MPCV) Orion. While the specific test objectives were met, a large base-driven test configuration such as this highlights several general concerns, for example: (i) if control is achieved at the interface between the component and the vehicle, can we be sure that the responses on the rest of the component will match? (ii) how closely do we need to match the flexibility of the interface for this to occur? (iii) what effect will nonlinearities have? And so forth. This white paper highlights the committee's view of the state-of-the-art in this area.

[1] The SDT CoP also recommended research in two other areas, 1.) Single axis shaker testing and environment definition and 2.) Shock testing. Those recommendations are elaborated in two separate white papers.

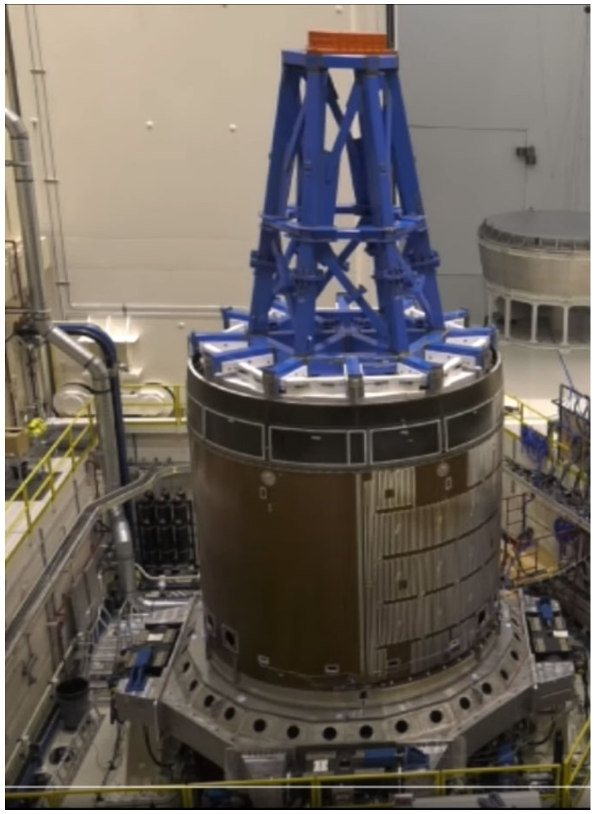

Figure 1: Picture of the E-STA undergoing a base shake test on MVF. A custom test fixture was designed to connect E-SSTA to the MVF shaker table.

1.1. State of the Art in Test Fixture Design

The purpose of the test fixture is to provide a mechanical connection between the test article and the vibration exciter(s) such that a realistic distribution of vibratory loads are observed across the structure of the test article. Group consensus is that current practice falls short of this goal; research is needed regarding the following issues that are encountered when designing test fixtures.

- **Field Dynamic Environment**: Test fixture design is dependent on the fidelity of the defined vibration environment and the objectives of the vibration test. A lack of understanding of this environment limits the success of a test. More research is needed to ensure that the field environment is rigorously defined with respect to the mounting, configuration, and impedance/flexibility of carrier platform. Guidance is needed to determine if and when multiple degree-of-freedom or distributed excitation is warranted. When is 1DOF sufficient? 3DOF? 6DOF? IMMAT? How do we integrate the test fixture design process into development of the field dynamic environment specification?

- **Vibration Control Considerations**: As additional DOF are considered and defined, additional complexity and flexibility will necessarily be incorporated into the test fixture design. For example, incorporating test fixture flexibility representative of the service boundary conditions makes it more difficult for the controller to meet the desired test specifications at all attachment points. This is a driving factor for increasing the number

of vibration exciters as inputs to the test article. How do we optimally design a test fixture/test setup to address this?

- **Risk Management Issues:** It is difficult to quantitatively correlate the results of a laboratory test to the expected risk of failure in the field (in-service) dynamic environment. Put another way the reliability of the test hardware has uncertainty that adds to its risk profile. Both over-test and under-test conditions may arise for a variety of reasons throughout the process of defining and executing a dynamic test. With respect to test fixture design, improper restraint of the test article has the potential of either creating or suppressing resonance conditions that result in unrealistically high or low strains on the test article. Some test fixture/part combinations may be more sensitive to the boundary conditions than others. For test articles with low safety margins or high risks associated with failure, it is critical to understand the potential for over- or under-test in a planned test approach. Each step in the test development process requires research and implementation guidance to define and manage risks.

- **Modeling and Simulation Techniques:** Iterative approaches between the test engineers and the developers of the test article may be required to optimize the test approach. Modeling techniques could be used to facilitate this process, but requires development and validation early in the process to ensure it is available when needed with sufficient fidelity to provide a reliable assessment.

- **Need for Published Case Studies**: The SDT CoP also found that the practice of dynamic testing often falls far short of the ideals set forth in the standards or used by expert practitioners. This may be in part because many of the most advanced dynamic tests involve classified, proprietary, or export-controlled hardware, and so there are relatively few published studies that elaborate on the lessons learned. The SDT CoP recommends funding publishable case studies that will educate the broader community regarding these issues.

Challenges with vibration control strategies can lead to delays as different test fixtures or configurations are attempted (i.e. the typical approach to deal with this is trial and error) or may require the test environment (i.e., the test specification) to be notched, resulting in some level of under-test. When that happens, one must often meet with the customer or stakeholder to get approval before the test specification can be changed (notched), and this can lead to significant delays. Over-testing and under-testing are thought to occur due to a mismatch in the impedances that the part experiences between the field and test. When this occurs, the accelerations and hence the stresses in the part during the test may differ significantly from those experienced in practice, causing failures in the test that would not be observed in the field, or vice versa. Because a lot of conservatism is often built into tests, when failures occur it is common for component designers to argue that the failure is “not relevant” rather than to feel that the failure is a meaningful indication that should prompt a redesign.

The above comments highlight many opportunities in test fixture design, such as increasing the use of modeling to predict the test and to correlate the test environment better to related failures, using a modal test to characterize the shaker+test fixture+test article system,

assuring adequate instrumentation is used to diagnose problems, etc. It was suggested that research may be partitioned into two extreme cases: (i) small/inexpensive/robust parts where the environments may not be well defined, and (ii) large/sensitive/complicated parts where the environments can be well characterized and less margin is available for over test. Research into smart testing could benefit both extremes.

While there are several standards that address dynamic environmental testing, there is a notable lack of information on test fixture design. The NASA standards [1] talk about test fixture design and the fixturing not affecting the component in the frequency range of interest, but do not go into more detail. The Shock and Vibration Handbook [2] discusses test fixture design in various places but does not address it in great detail. Various national standards such as MIL-STD-810H [3] also recognize the issues with impedance mismatches yet minimal guidance is provided. It is recognized that achieving perfect impedance matches in the laboratory environment is not practical, especially when addressing very large structures such as the example discussed in Figure 1. However, through the implementation of smart dynamic testing principles such as integration of modeling and careful instrumentation practices, the integrated model/test approach has the potential to optimize the impedance match to the degree possible, to reduce significantly the test duration and thereby the cost required to complete a dynamic test cycle.

The concept of Smart Dynamic Testing is highly correlated to the concept of the Integrated Test Analysis Process (ITAP) described by Coppolino [4]. As in the case of the ITAP, the desire in a vibration test will be to minimize the amount of test fixture kinetic energy imparted onto the test payload of interest. While reference [4] provides a thorough mathematical based discussion of the topic, the SDT committee agreed that research is needed to define and document practical test fixture design principles spanning the wide range of applications of interest. At present, one can find multiple technical papers on various aspects of test fixture design and multiple vendors willing to provide vibration test fixture design and fabrication services, however, developing a comprehensive standard guidance document on the topic has been challenging.

1.2 Quantifying the Cost Impact of Fixture Design on Laboratory Vibration Testing

Understanding the risks of unrealistic laboratory test conditions is essential to quantifying the risks of an improperly designed test fixture/setup. In reality the costs of the status-quo on the testing and development cycle are far higher yet difficult to quantify. Failed qualification tests often lead to schedule delays, which can be incredibly costly. For example, on a billion-dollar satellite the capital costs alone may be in the tens to hundreds of thousands of dollars per day, so that a several month delay can have significant financial impact on a program. It is also difficult to quantify the number of man hours spent by engineers, contract negotiation teams, etc., in dealing with failed tests, either for re-design, performing analysis to remove conservatism from the environments, or otherwise.

As mentioned previously, it is not uncommon for the vibration test fixture to account for over 50% of the cost of a laboratory vibration test. Efforts to improve fidelity and to manage costs of dynamic tests are driving the need for further research and implementation guidance into

test fixture design and analysis processes. As part of the CoPs deliberations, eight organizations completed a survey on various aspects of environment testing. Of those eight, four can be considered very heavy users, and provide an indicative case study. Sandia National Labs, Naval Surface Warfare Center – Dahlgren Division, Redstone Test Center and the Kansas-City National Security campus each have between 4 and 8 single- and multi-axis test cells with large shakers that run nearly continuously. A consensus of respondents indicated that a more integrated approach to the development of a dynamic test fixtures/setups is required to account fully for the planned service environment and mechanical impedance associated with the service conditions.

The costs reported by these facilities associated with the design, fabrication, setup, and verification of a new dynamic test fixture/setup varies as a function of the size and configuration of the excitation systems. For small, single axis tests, dynamic test costs are typically on the order of $10-100k. For large, multi-axis vibration test configurations, costs for dynamic testing are on the order of $100k-$1M. In rare cases, costs are well in excess of $1M. In any of these cases, one of the primary cost drivers is associated with the development and implementation of the test fixture and it is not uncommon for 50% or more of the cost of the dynamic test to be associated with the test fixture and system integration. Similarly, the dynamic test schedules are heavily impacted by test fixture and setup considerations.

Recent success in both base driven and distributed MDoF excitation systems have illustrated new opportunities both to improve the fidelity of the dynamic test environment while also reducing the cost and schedule of the test program. Based on these successes, further research in these areas has a high potential to both reduce risks and costs associated with dynamic tests.

2. CONCLUSIONS

A committee of experts in the area of dynamic environment testing recommends that research is needed regarding development of test fixture design processes for dynamic environment testing. The smart dynamic testing paradigm focuses on opportunities to merge test and analysis and so the time is ripe to produce significant advances. The costs of maintaining the status quo are high, especially if one considers the costs to schedule when unrealistic failures occur due to test configurations/requirements that are not representative of the actual environment. The proposed research has a strong probability of improving the state-of-the-art and mitigating these risks.

References:

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[3] Mil-Std-810H, Methods 514 and 527, 31 January 2019.
[4] Robert N. Coppolino, "The Integrated Test Analysis Process for Structural Dynamic Systems", Morgan and Claypool Publishers, 2020, ISBN: 9781681736839.